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SPECTRAL ESTIMATION OF ALFALFA BIOMASS UNDER CONDITIONS OF VARIABLE CLOUD COVER

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1. INTRODUCTION

Conventional methods for estimating plant biomass have serious drawbacks which occasionally limit their use in biological research and monitoring programs. First of all, most methods are very labor intensive, tedious and time consuming to perform. The size, number and frequency of samples needed to detect statistically significant differences between treatments are often much larger than feasible due to budget, labor, storage and oven space constraints. Second, the requirement for drying the samples precludes the immediate use of biomass data in any real time decision making process. Thus, information which has potential use for guiding future sampling or assessing the efficacy of different treatments is usually not available until several days after it was collected. Perhaps most importantly, destructive sampling is usually not appropriate in small plots because the removal of some individuals of the population is likely to alter the effects of the treatment on the remainder.

A non-invasive, remote sensing technique that uses plant canopy reflectance to estimate biomass avoids these problems and provides scientists with an efficient tool for research and management. The physical basis for this approach derives from the spectral reflectance properties of plant canopies and their underlying soil. Healthy green plant foliage has a very low reflectance (2-5%) in the visible portion of the spectrum. In the near-infrared (NIR) portion of the spectrum however, 50-60% of the incident light is reflected by vigorous green vegetation. By contrast the reflectance characteristics of most agricultural soils are usually quite different. Reflectance of visible light from soils may be up to an order of magnitude greater than that from green plants, while in the NIR it might be only half that of the plants.

Vegetation indices (VIs) refer to multiband combinations of target reflectances that maximize the differences in spectral information between plant canopies and soils. They can take the form of simple band ratios, normalized differences between bands or linear combinations of bands which have been optimized to yield specific information about a particular target of interest (Tucker 1979, Richardson and Wiegand 1977). The simple ratio of NIR/Red reflectances or a normalized difference between these bands [(NIR-Red)/(NIR+Red)] are common examples of VIs useful for biomass assessment.

Several earlier studies have demonstrated the usefulness of VIs in estimating percentage cover, drought-induced reductions in biomass and daily growth of alfalfa (Tucker *et al.* 1980, Kirchner *et al.* 1982, and Pinter 1983). Although band ratio VIs are particularly sensitive to changes in the angle of solar irradiance and view angle of the sensor, they are relatively unresponsive to differences in surface moisture content of the soil. They also have the distinct benefit of retaining much of their information content under conditions of varying topography and illumination intensity (Jackson *et al.* 1980, Pinter *et al.* in press). This latter advantage is a particularly important feature if remote measurements of canopy reflectance are to be routinely used as reliable estimators of biomass in regions where cloud cover is the rule rather than the exception.

The following report describes an experiment wherein alfalfa canopy reflectances in two visible and two NIR regions of the spectrum were measured daily with a ground-based portable radiometer. Our objectives were: 1) to establish relationships between biomass and various VIs calculated from canopy reflectances and 2) to examine the effect of variable sky and cloud cover conditions on those relationships.

2. MATERIALS AND METHODS

2.1 Experimental Site, Cultural Practices and Irrigation Treatments

This experiment was conducted in one-year old experimental field plots of alfalfa (*Medicago sativa* L. cv Lew) located at the U.S. Water Conservation Laboratory in Phoenix, AZ (Lat 33°26'N, Long 112°01'W). The soil was an Avondale loam [fine-loamy, mixed (calcareous), hyperthermic Anthropic Torrifluvent]. Seeds were broadcast planted at a rate of 43.5 kg ha^{-1}. Stands had random plant distribution. During the experiment we relate here, there were 4 different irrigation treatments based on timing and frequency of irrigation. These ranged from wet (2 irrigations per harvest cycle) to dry (no irrigations per cycle). After each harvest, deficit irrigation treatments were rotated to different plots so that plants were not exposed to drought stress during consecutive regrowth periods.

2.2 Biomass Sampling

Above-ground plant biomass was estimated from four, $0.25m^2$ circular samples taken at 3 or 4 day intervals over two harvest cycles during the spring in 1985. Plants were cut by hand in the field with a curved knife leaving a stubble height of 2 to 3 cm. Plant material was dried in an oven for at least 48h at 60-70°C. Dry biomass ($g\ m^{-2}$) was calculated as the sum of dry weights for the four $0.25m^2$ samples. Since the reflectance data and biomass were sampled on a different time scale, it was desirable to estimate biomass data for every day that reflectances were measured. This was achieved by applying a second degree sliding polynomial curve fitting procedure to the twice-weekly plant samples and interpolating biomass data for those days.

2.3 Radiometric Measurements

Crop canopy reflectances were measured using an Exotech Model 100A* portable radiometer equipped with 15° field-of-view optics and spectral bandpass filters similar to those of the Landsat Multispectral Scanner. Only data from the Red (0.6 to 0.7μm) and NIR (0.8 to 1.1μm) wavebands will be discussed in this report. The radiometer was handheld over 1 by 9m target areas in each plot. Access to targets was provided by east-west boardwalks that were elevated about 0.2m above the surface of the soil. All measurements were taken with the radiometer extended at arm's length towards the south and approximately 1.75m above the soil surface. The sensor was pointed in a nadir direction, with each lense viewing an area approximately 0.3m in diameter when the plants were 0.5m in height.

Multispectral observations were made daily from 1 April until 4 June 85 at a morning time period corresponding to a constant solar zenith angle of 57°. Data were collected regardless of sky or cloud conditions. Analog signals from the radiometer were recorded on a portable data logger (Polycorder*, Omnidata International, Inc.) which also indicated the time when measurements were taken. Reflectances were calculated as the ratio of radiances measured over each alfalfa target to irradiances inferred from a time-based linear interpolation of data collected at 6-8 minute intervals over a 0.6 by 0.6m, horizontally positioned, calibrated, painted $BaSO_4$ reference panel. Correction factors were applied to the $BaSO_4$ data to compensate for the non-lambertian reflectance properties of the panel at a solar zenith of 57° (Jackson et al. in press). Twelve measurements in each plot were combined to yield an average reflectance for each band. The entire measurement sequence over 18 experimental plots required about 15 minutes to complete. The data we report here were collected from 4 plots; one replicate of each irrigation treatment during 2 consecutive harvest cycles.

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* Trade names and company names are included for the benefit of the reader and do not constitute an endorsement by the U.S. Department of Agriculture.

3. RESULTS AND DISCUSSION

3.1 Relationship Between Biomass and Spectral Reflectance

The sensitivity of a spectral VI to alfalfa vegetation during clear sky conditions is shown in Figure 1. Here interpolated daily values of total dry biomass are graphed versus the ratio of NIR (0.8 to 1.1μm) to Red (0.6-0.7μm) canopy reflectances. Data from all irrigation treatments are presented in this

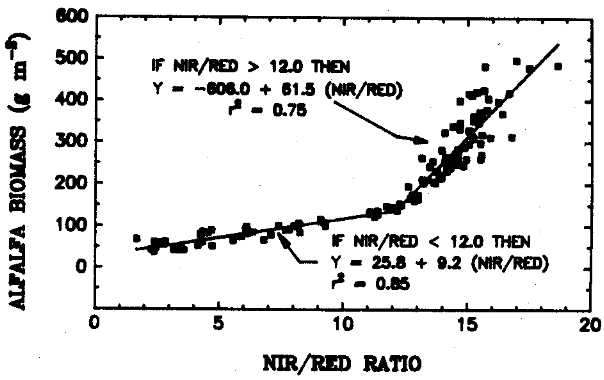

Fig. 1. Interpolated alfalfa biomass versus the ratio of NIR to Red reflectances measured on days when the solar disk was not constructed by clouds. All data were collected at a solar zenith angle of 57°.

figure, suggesting that the relationship is similar for both water-stressed and well-watered alfalfa. A conspicuous feature of these data was the inflection point appearing when the VI was approximately 12. This corresponded to a biomass of 125-150 $g\ m^{-2}$ and a time when canopy closure reached 100%. Accordingly, we have chosen to describe the overall relationship by two highly significant linear relations which intersect at the 100% canopy cover point.

Prior to complete canopy cover the ratio index showed high sensitivity to increasing amounts of vegetation, with minimal scatter around the trend line. A small increment of growth elicited a relatively large increase in the VI. Our daily VI data during this early regrowth period also revealed day-to-day growth very clearly. In fact, where measurements were made morning and afternoon at similar solar zenith angles on the same day, it was even possible to see changes in the VI which were associated with shorter term increases in biomass (not shown).

After the developing canopy completely covered the soil, the slope of the relation between biomass and the index increased sharply. A larger change in biomass was required to evoke a unit increase in the vegetation index. The amount of scatter in the data also increased markedly and the variation appeared to rise proportionately with increasing biomass. Several hypotheses can be advanced to account for this increase in variability. 1) Because the denominator of the ratio VI was very small at high biomass levels, slight differences in the amount of shadowed canopy viewed by the radiometer's optics and/or minor measurement errors were translated into relatively large changes in the VI. 2) A second reason for increased variability is that this index was sensitive to changes in canopy architecture. As the plants increased in biomass they became more susceptible to day-to-day rearrangement and lodging by the wind. 3) It was also likely that the index responded more to changes in projected green leaf area than total biomass per se. Because severe water stress induced leaflet folding and lower leaf drop in the drier irrigation treatments this may have contributed additional variability.

3.3 Effect of Cloud Cover on Spectral Biomass Estimates

Extreme variation in single band crop canopy reflectances result from cloud interference with direct beam solar irradiance (Lord et al. 1985). However, field observations of sugar cane (Jackson et al. 1980) and wheat (Pinter et al. in press) have revealed that ratio VIs are minimally sensitive to changing illumination intensities occurring when clouds pass in front of the sun. This is because both bands tend to behave in a similar fashion when direct beam solar irradiance is reduced. Inasmuch as spectral reflectance measurements were collected as often as possible during this experiment and qualitative observations of sky conditions were also made, it was possible to sort the alfalfa reflectance data according to the cloud conditions. This provided an excellent opportunity to test the hypothesis that reflectances and derived vegetation indices could be used to predict biomass during complete overcast and intermittant sun and shade conditions which have traditionally been considered unsuitable for obtaining high quality measurements.

Figure 2 shows NIR/Red VI values obtained on days when the sun was obscured by varying degrees of cloud cover (plus symbols) superimposed on the regression lines derived from clear day data. The variation exhibited by the data points for cloudy conditions appear to be scattered randomly above and below the trend lines and are no more variable than the data collected under clear skies. The normalized difference behaved in a similar fashion (not shown). This is encouraging from a practical point of view because it implies that band ratioing techniques can be used to predict biomass under reduced irradiance conditions caused by constant and intermittant cloud cover.

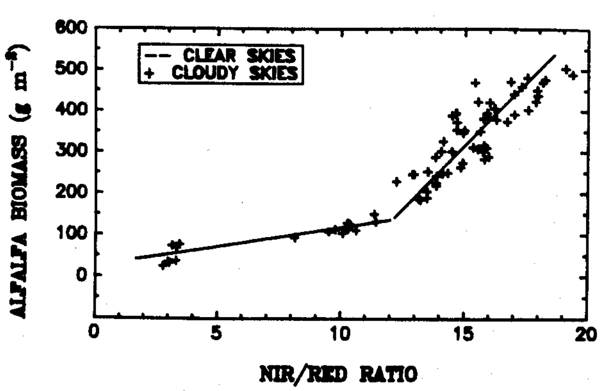

Fig. 2. Interpolated alfalfa biomass versus the ratio of NIR to Red reflectances. Days when clouds obscured the solar disk are superimposed on the trend lines for cloud-free data of Figure 1.

Single band canopy reflectance data were also well correlated with total biomass levels when illumination conditions were constant and the sun was unobstructed (solid square symbols in Figures 3a and b). However, cloud

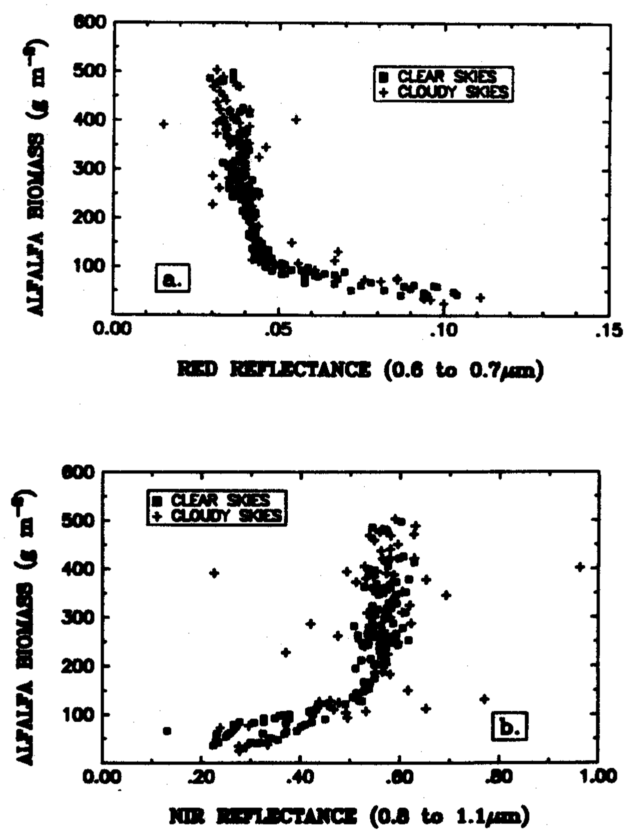

Fig. 3. Interpolated alfalfa biomass versus Red and NIR reflectances.

interference with the direct beam of the sun during measurement of the canopy radiance and/or irradiance levels introduced considerable scatter into the relationship (plus symbols). This precludes their use for predictive purposes under all but optimum, clear sky conditions.

In our study, alfalfa reflectance factors were computed from sequential estimates of sky and solar irradiance made shortly before and after canopy measurements. This is the procedure that is most likely to be used in the field for assessing canopy characteristics because it is simple, very rapid and requires only a single radiometer. If simultaneous estimates of irradiance obtained with a second radiometer (Duggin and Cunia, 1983) were used to calculate reflectances, single band reflectances might have performed better under variable cloud conditions.

The high degree of variability we observed in single band reflectance factors suggested that linear combinations of several bands would also be inadequate for predicting biomass under non-clear sky conditions. Unlike ratio VIs where proportional changes in each band were cancelled, VIs such as the Perpendicular Vegetation Index and Greenness were affected substantially by absolute changes in reflectance of component bands. Figure 4,

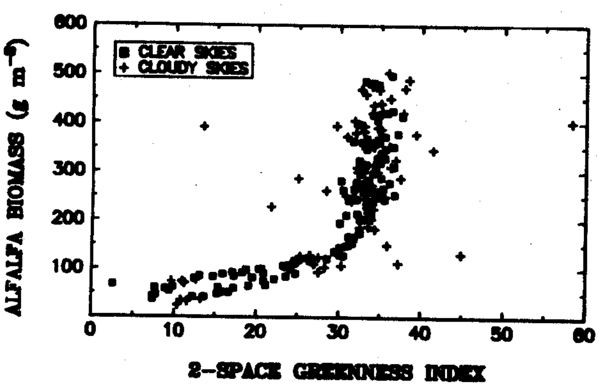

Fig. 4. Interpolated alfalfal biomass versus a linear combination VI. (Greenness = -76.1 * Red + 64.9 * NIR).

for example, shows that the performance of a 2-space Greenness index derived from the Red and NIR alfalfa reflectances (Jackson, 1983) was seriously degraded by clouds. Linear combination VIs should be limited to clear sky conditions or situations where simultaneous estimates of irradiance are available for computing reflectances.

4. CONCLUSIONS AND IMPLICATIONS

Alfalfa biomass can be estimated satisfactorily using hand-held spectral radiometers and a vegetation index calculated as the ratio of NIR to Red canopy reflectances. Analysis of canopy reflectance data collected at a solar zenith angle of 57° showed no appreciable loss of information on biomass when clouds interfered with the direct beam solar irradiance, provided a ratio type vegetation index was employed. Single band reflectances and linear combinations of several bands, while highly correlated with biomass during clear sky conditions, were not useful for predicting biomass under conditions of variable cloudiness.

This ground-based remote sensing approach offers a simple, rapid alternative to conventional biomass sampling. Unlike methods which have been used in the past, this technique is very cost effective and provides data immediately for analysis or input into predictive growth or irrigation models. The capability of measuring the same canopy repetitively without disturbing the plants makes this technique ideal for small plot research.

5. ACKNOWLEDGMENTS

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